AFRL-AFOSR-VA-TR-2018-0327

Expanding the Reach of Nonlinear Optimization

Stephen Robinson
UNIVERSITY OF WISCONSIN SYSTEM

08/13/2018
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA2
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
11-08-2018	Final Report	1 Jun 2015 - 31 May 2018

4. TITLE AND SUBTITLE
Expanding the Reach of Nonlinear Optimization

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-15-1-0212

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ferris, Michael C.
Robinson, Stephen M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Board of Regents of the University of Wisconsin System
University of Wisconsin-Madison, Research & Sponsored Programs
21 N. Park St Ste 6401
Madison, Dane County, Wisconsin 53715-1218

8. PERFORMING ORGANIZATION REPORT NUMBER
MSN180747

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 N. Randolph St, Ste 325
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A. Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Affine variational inequalities (AVI) are an important problem class that generalize systems of linear equations, linear complementarity problems and optimality conditions for quadratic programs. Among other things, they are models for the equilibrium constraints used in MOPEC and MPEC, where the acronym MOPEC means “multiple optimization problem with equilibrium constraints,” and MPEC means “mathematical program with equilibrium constraints.” Therefore, solution methods for AVI are important elements in dealing with MOPEC and MPEC. The work done under this grant included development and testing of the algorithm PATHAVI, which uses a structure-preserving pivotal approach to process (solve or determine infeasible) large-scale sparse instances of an AVI problem efficiently, with theoretical guarantees and at high accuracy. PATHAVI implements a strategy that is known to process models with good theoretical properties without reducing the problem to specialized forms, since such reductions may destroy structure in the models and can lead to very long computational times.

15. SUBJECT TERMS
Optimization; Nonlinear programming; Affine variational inequalities; MPEC (Mathematical program with equilibrium constraints; MOPEC (Multiple optimization problem with equilibrium constraints); spatially coupled systems; Cournot-Nash-Walras equilibrium; solvers for affine variational inequality problems. Applications in planning and management.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Robinson, Stephen M.
U	U	U	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 608.263.6862

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Adobe Professional 7.0

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FINAL REPORT

AFOSR Grant FA9550-15-1-0212

Expanding the Reach of Nonlinear Optimization

Michael C. Ferris and Stephen M. Robinson
Principal Investigators

Period covered: 1 June 2015 - 31 May 2018

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Contents

1 Introduction

This grant covered a period of three years, from 1 June 2015 to 31 May 2018. We have organized this final report in three main sections, one for each year of support. Each section provides information about research activities conducted in the corresponding year and publication activity resulting from the research.

2 Activities

2.1 Change of Program Manager

The principal investigators were notified that as of 1 June 2016 the AFOSR Program Manager changed from Dr. Fariba Fahroo to Dr. Jean-Luc Cambier.

2.2 Objectives

The objectives of this research did not change from the final version of the original proposal, which proposed a three-year period of performance, 1 January 2015 – 31 December 2017, with one FTE month's support per year for each of the two proposers and six FTE months' research assistant work per year. This period of performance was revised during subsequent negotiations to the three-year period 1 June 2015 – 31 May 2018.

The main objectives were stated as follows. The acronym MOPEC means "multiple optimization problem with equilibrium constraints," and MPEC means "mathematical program with equilibrium constraints."

1. Clarify and develop the mathematical structure of deterministic MOPECs and of subsidiary problems that arise from MOPEC use.

2. Devise, justify, and test efficient algorithms for numerical solution of the problems in Objective 1.

3. Use the results of work under Objectives 1 and 2 to discover properties and behavioral characteristics of MOPECs that could be helpful in designing or regulating the systems they describe.

2.3 June 2015 – May 2016

- We continued to investigate the use of optimization models within the electrical power industry. Sophisticated optimization algorithms enable solutions to be obtained much more efficiently. The paper [31] shows how to build an overall optimization model that incorporates decision making at multiple time scales. In this paper, we formulate a long-term planning model of transmission line expansion based on balancing investment cost and reducing consumer cost. We achieve this by formulating a hierarchical framework that is sensitive to different agents operating on different timelines, the relationships of which may be competitive, cooperative or somewhere in between. The advantage of this framework is that while it captures the complexity of long-term decision making, it maintains clarity of information flow between models, agents and timelines. For our purposes, we introduce an equilibrium model that combines grid operational concerns with the short-term competitive behavior of generation firms. An iterative solution technique is proposed to provide a Nash solution where each optimization problem is solved globally. This solution is then used to inform an overarching transmission planning model that we solve using derivative-free optimization. Using a decongested network as a benchmark, numerical results indicate a non-alignment of the objectives of planning and operational entities, whereby easing line congestion may not offer monetary benefits to the wholesale consumer.

- Extensions of models to facilitate new economic principles were given in [32] and [9]. The first paper proposed to open up the bidding structure to allow for more forms of bids that reflect realistic demand characteristics and behaviors. We proposed additional bid types that allow time-shiftable demand to better express its value, and thus to elicit demand response in the most natural way – direct participation in the market. In the second paper [9], we outlined a computational approach for efficiently solving an MPEC problem that implements a FERC policy for demand response. The paper was in review for a long time since the policy itself was controversial, and the paper was finally accepted when the Supreme Court upheld the rule, thereby creating a need for computational techniques to implement it.

- In conjunction with Elizabeth Ritz at Stanford, we revisited and applied some of the complementarity models developed under predecessor AFOSR grants to more realistic and larger scale instances of fault geometry. The solution of these instances required changes to the actual models, minor extensions of some of the features captured, and solution of much larger practical instances. The published paper [33] documents this computational study.

- We continued to investigate the use of optimization techniques within (spatially) coupled systems for environmental issues. The work involved optimization models of coupled systems including those for fish barrier removal (see [3]), joined with mechanisms to allow decision makers to collectively understand and adapt decision processes (see [1]). Key contributions involved building large scale optimization models of interacting systems using a hierarchical approach, along with tools to enable domain specialists to adapt data and interfaces to improve overall system optimization.

- After the day-ahead market is cleared and before the real-time market is started, Independent System Operator (ISO) uses a Reserve Adequacy Assessment (RAA) process to determine supplemental unit commitments to meet the hourly forecasted load and reserve requirements for the next operating day. The paper [5] presented a stochastic programming model for the RAA process to manage the net load uncertainty. Due to the large size of ISO systems and the increasing net-load variability caused by increasing penetration of renewable resources, the problem is computationally challenging. We developed an effective scenario reduction technique, Derandomization (or Derand), to identify a small number of scenarios that extract key and unbiased information from the distributions of uncertain variables. Numerical testing results showed that the stochastic model with only 3 or 5 scenarios outperforms its deterministic counterpart by a significant margin, yielding lower expected cost and fewer constraint violations. Results also showed that the Derand method outperforms several conventional scenario reduction methods, and the solution quality is comparable to the cost based scenario-reduction technique but with less computational effort.

- The paper [2] developed a new implementation of a Benders' method for solving a large scale security constrained electricity dispatch problem. This paper models the security-constrained economic dispatch problem with post-contingency corrective actions. At the time of this development, the work was under consideration by ISO-NE as a new methodology for their daily operations due to the speed and the additional features that a sophisticated implementation allow. In the nonlinear AC setting, the model is a large-scale nonconvex problem and is difficult to solve. A novel solution approach was proposed to deal with the scale and nonconvexity issues separately and effectively. The key extension proposed in [6] was to approximate the nonconvex AC feasibility problem with its semidefinite programming (SDP) relaxation and use these SDP models as a convex subproblem within a Benders' decomposition framework. Numerical experiments demonstrated the superior solution quality of this approach and its tractability for IEEE test cases, while suggesting future work for computational improvements on large-scale problems.

- Large-scale electric power system analysis depends upon representation of vast numbers of components whose individual models must be populated with parameters. The challenge of populating such component models is particularly apparent in optimal power flow applications, in which incorrect parameters and/or constraint limits can yield overall system representations with either unrealistically large feasible regions or an empty feasible set. Unfortunately, many data sets, particularly those of publicly available test cases, were originally developed to illustrate simpler power flow only applications, and may contain unrealistic values or wholly omit important constraint limits. The paper [7] describes engineering-based approaches to obtain credible estimates for parameters and limits associated with line-flow constraints and generator capability curves, as may be employed in a number of steady state analyses such as the optimal power flow. These can substitute for missing or unrealistic data in test systems for which more fully detailed, "real-world" component specifications and limits are not available, and thereby make such test systems more valuable as research tools.

- The correspondence of competitive partial equilibrium with a social optimum is well documented in the welfare theorems of economics. These theorems can be applied to single-period electricity pool auctions in which price-taking agents maximize profits at competitive prices, and extend naturally to standard models with locational marginal prices. In hydro-thermal markets where the auctions are repeated over many periods, agents seek to optimize their current and future profit accounting for future prices that depend on uncertain inflows. This makes the agent problems multistage stochastic optimization models, but perfectly competitive partial equilibrium still corresponds to a social optimum when all agents are risk neutral and share common knowledge of the probability distribution governing future inflows. The situation is complicated when agents are risk averse. In this setting, the paper [8] showed under mild conditions that a social optimum corresponds to a competitive market equilibrium if agents have time-consistent dynamic coherent risk measures and there are enough traded market instruments to hedge inflow uncertainty. We illustrated some of the consequences of risk aversion on market outcomes by using a simple two-stage competitive equilibrium model with three agents.

- The paper [4] deals with reduction of an affine variational inequality posed over a polyhedral convex set in n-dimensional Euclidean space. It is often the case that this underlying set has dimension less than n, or has a nontrivial lineality space, or both. We showed that when the variational inequality satisfies a well known regularity condition, we can reduce the problem to the solution of an affine variational inequality in a space of smaller dimension, followed by some simple linear-algebraic calculations. The smaller problem inherits the regularity condition from the original one, and therefore it has a unique solution. The dimension of the space in which the smaller problem is posed equals the rank of the original set: that is, its dimension less the dimension of its lineality space.

2.4 June 2016 – May 2017

- The paper [11] gives a short proof of a key lemma about polyhedral convex sets. Suppose C is such a set in $\mathbb{R}^n$ and that $z^* \in \mathbb{R}^n$ is a point such that the inner product $\langle z^*, c\rangle$ has a finite maximum over $c \in C$. The set M of maximizers of $\langle z^*, \cdot\rangle$ on C is then a nonempty face F of C. The lemma says that there is a neighborhood N of z^* such that if $y^* \in N$ then the set of maximizers on C of $\langle y^*, \cdot\rangle$ is the set of maximizers on F of $\langle y^*, \cdot\rangle$. Thus, small perturbations of the point z^* produce sets of maximizers on C that always remain in F. This lemma has important applications to, among other problems, the behavior of affine variational inequalities.

- In [10], we investigate a model of Cournot-Nash-Walras (CNW) equilibrium where the Cournot-Nash concept is used to capture equilibrium of an oligopolistic market with non-cooperative players/firms who share a certain amount of a so-called rare resource needed for their production, and the Walras equilibrium determines the price of that rare resource. We prove the existence of CNW equilibria under reasonable conditions and examine their local stability with respect to small perturbations of problem data. In this way we show the uniqueness of CNW equilibria under mild additional requirements. Finally, we suggest some efficient numerical approaches and compute several instances of an illustrative test example.

- We continued to investigate the use of optimization techniques within (spatially) coupled systems for environmental issues. The paper [12] considers the identification of areas within a landscape that facilitate incompatible species habitat conservation.

  The work in [15] extends previous models from this grant involving optimization models for fish barrier removal. Structures that block movement of fish through river networks are built to serve a variety of societal needs, including transportation, hydroelectric power, and exclusion of exotic species. Due to their abundance, road crossings and dams reduce the amount of habitat available to fish that migrate from the sea or lakes into rivers to breed. The benefits to fish of removing any particular barrier depends on its location within the river network, its passability to fish, and the relative position of other barriers within the network. Balancing the trade-offs between ecological and societal values makes choosing among potential removal projects difficult. To facilitate prioritization of barrier removals, we developed an online decision support tool (DST) with three functions: (1) view existing barriers at various spatial scales; (2) modify information about barriers, including removal costs; and (3) run optimization models to identify portfolios of removals that provide the greatest amount of habitat access for a given budget. Our DST enables organizations to develop barrier removal priorities based on cost-effectiveness in restoring aquatic connectivity.

- In the computer design industry, the paper [13] shows how to use techniques from mathematical optimization to manage the design complexity of on-chip network problems. We show how three previously studied design problems–memory controller placement, resource allocation in heterogeneous on-chip networks, and the combination of these two problems–can be formulated as mathematical optimization problems. Standard solvers can then determine optimal solutions in minutes, rather than the hours or days needed for brute force, randomized search, or genetic algorithms. Detailed simulation–using synthetic traffic, micro-benchmarks, and real life applications–show that our mathematically optimal designs provide better performance than did previous solutions. Our work provided further evidence towards the suitability of optimization models in searching/pruning architectural design space.

- In [14] we looked into conventions for naming in scientific codes and their long term resilience. Names in programming are vital for understanding the meaning of code and big data. We define Code2Brain-Interfaces (C2BIFs) as maps in compilers and brains between meaning and naming syntax, helping to understand executable code. While working towards an Evolvix syntax for general purpose programming that makes accurate modeling easy for biologists, we observed how names affect C2BIF quality. We present the Evolvix BEST Names concept for reducing Naming priority conflicts, test it on a real challenge by Naming subfolders for the Project Organization Stowing Tool (POST) system, and provide Naming questionnaires designed to facilitate C2BIF debugging by improving names used as keywords in a programming language.

- The paper [16] investigates a new class of congestion games, called Totally Unimodular Congestion Games, in which the strategies of each player are expressed as binary vectors lying in a polyhedron defined using a totally unimodular constraint matrix and an integer right-hand side. We study both the symmetric and the asymmetric variants of the game. In the symmetric variant, all players have the same strategy set, i.e. the same constraint matrix and right-hand side. Network congestion games are an example of this class. Fabrikant et al. proved that a pure Nash equilibrium of symmetric network congestion games can be found in strongly polynomial time, while the asymmetric network congestion games are PLS-complete. We give a strongly polynomial-time algorithm to find a pure Nash equilibrium of any symmetric totally unimodular congestion game. We also identify four totally unimodular congestion games, where the players' strategy sets are matchings, vertex covers, edge covers and stable sets of a given bipartite graph. For these games we derive specialized combinatorial algorithms to find a pure Nash equilibrium in the symmetric variant, and show the asymmetric variant is PLS-complete.

- Conservation planning aims to optimize outcomes for select species or ecosystems by directing resources toward high-return sites. The possibility that local benefits might be increased by directing resources beyond the focal area is rarely considered. In [17], we present a case study of restoring river connectivity for migratory fish of the Great Lakes Basin by removing dams and road crossings within municipal jurisdictions versus their broader watersheds. We found that greater river connectivity could often be achieved by considering both intra-jurisdictional and extra-jurisdictional barriers. Our study underscores the local-scale benefits of broadening restoration investments, especially for decision makers of the Great Lakes Basin and contributes to a discussion of appropriate and efficient scales of conservation planning.

- Affine variational inequalities (AVI) are an important problem class that generalize systems of linear equations, linear complementarity problems and optimality conditions for quadratic programs. The paper [18] describes PATHAVI, a structure-preserving pivotal approach, that can process (solve or determine infeasible) large-scale sparse instances of the problem efficiently, with theoretical guarantees and at high accuracy. PATHAVI implements a strategy that is known to process models with good theoretical properties without reducing the problem to specialized forms, since such reductions may destroy structure in the models and can lead to very long computational times. We demonstrated formally that PATHAVI implicitly follows the theoretically sound iteration paths, and can be implemented in a large scale setting using existing sparse linear algebra and linear programming techniques without employing a reduction. We also extended the class of problems that PATHAVI can process. The paper demonstrated the effectiveness of our approach by comparison to the PATH solver used on a complementarity reformulation of the AVI in the context of applications in friction contact and Nash Equilibria problems. PATHAVI is a general purpose solver, and is freely available under the same conditions as PATH.

2.5 June 2017 – May 2018

- Typical formulations of the optimal power flow (OPF) problem rely on what is termed the bus-branch model, with network electrical behavior summarized in the Ybus admittance matrix. From a circuit perspective, this admittance representation restricts network elements to be voltage controlled and limitations of the Ybus have long been recognized. A fixed Ybus is unable to represent an ideal circuit breaker, and more subtle limitations appear in transformer modeling. In power systems parlance, more detailed approaches to overcome these limitations are termed node-breaker representations, but these are often cumbersome, and are not widely utilized in OPF. In the paper [19], we develop a general network representation adapted to the needs of OPF, based on the Sparse Tableau Formulation (STF) with following advantages for OPF: (i) conceptual clarity in formulating constraints, allowing a comprehensive set of network electrical variables; (ii) improved fidelity in capturing physical behavior and engineering limits; (iii) added flexibility in optimization solution, in that elimination of intermediate variables is left to the optimization algorithm. The STF is then applied to OPF numerical case studies which demonstrate that the STF shows little or no penalty in computational speed compared to classic OPF representations, and sometimes provides considerable advantage in computational speed.

- The paper [20] examines three different formulations of AC optimal power flow problems and compares performance of well-established, general purpose optimization algorithms for each, over different initial conditions. Polar power-voltage, rectangular power-voltage and rectangular current-voltage are formulated to evaluate ACOPF solution characteristics. The formulations here maintain line flows as explicit variables, and employs summations of these quantities to impose conservation conditions at each node. Two representations of line thermal limits are considered, one using real power (to allow comparisons to DC power flow approximations), and a more physically-based, ampacity limit using current magnitude. Nonlinear generator capability curves are represented (D-curves), including options to allow active and reactive limits dependent on generator voltage. A uniform objective function is used throughout, that of minimizing quadratic generator operating cost curves. Numerical performance case studies are performed for these formulations over six different classes of initial conditions, evaluating computational time and also robustness of convergence.

- When cells compete for nutrients, those that grow faster and produce more offspring per time are favored by natural selection. In contrast, when cells need to maximize the cell number at a limited nutrient supply, fast growth does not matter and an efficient use of nutrients (i.e. high biomass yield) is essential. This raises a basic question about metabolism: can cells achieve high growth rates and yields simultaneously, or is there a conflict between the two goals? To study the conditions for such rate-yield trade-offs, we considered in [21] a kinetic model of *E. coli* central metabolism and determined flux distributions that provide maximal growth rates or maximal biomass yields. Using a new modeling method called Enzymatic Flux Cost Minimization (EFCM), we predict cellular growth rates and find that growth rate/yield trade-offs and the ensuing preference for enzyme-efficient or substrate-efficient metabolic pathways are not universal, but depend on growth conditions such as external glucose and oxygen concentrations.

- Conservation practitioners face difficult choices in apportioning limited resources between rare species (to ensure their existence) and common species (to ensure their abundance and ecosystem contributions). In [22], we quantified the opportunity costs of conserving rare species of migratory fishes in the context of removing dams and retrofitting road culverts across 1,883 tributaries of the North American Great Lakes. Our optimization models show that maximizing total habitat gains across species can be very efficient in terms of benefits achieved per dollar spent, but disproportionately benefits common species. Conservation approaches that target rare species, or that ensure some benefits for every species (i.e., complementarity) enable strategic allocation of resources among species but reduce aggregate habitat gains. Thus, small habitat gains for the rarest species necessarily come at the expense of more than 20 times as much habitat for common ones. These opportunity costs are likely to occur in many ecosystems because range limits and conservation costs often vary widely among species. Given that common species worldwide are declining more rapidly than rare ones within major taxa, our findings provide incentive for triage among multiple worthy conservation targets.

- Invasive species are a leading global cause of native biodiversity decline. Controlling invasive species is critical for conservation, but involves trade-offs such as diversion of resources away from other efforts and unintended negative effects. In [23], we present a compelling case with global relevance to balancing conservation outcomes. The intensity and duration of sea lamprey control in the North American Great Lakes creates a unique opportunity to understand best approaches to balance the negative and positive consequences of conservation. We show one important case where control of an invasive species has greatly infringed on potential benefits to desirable species with high conservation and monetary restoration costs. Consequently, our results emphasize the importance of research on the biology and geography of target species and of using multiple complementary approaches to conservation to benefit desirable species while minimizing the spread of invasives.

- A hallmark of industrialization is the construction of dams for water management and roads for transportation, leading to fragmentation of aquatic ecosystems. Many nations are striving to address both maintenance backlogs and mitigation of environmental impacts as their infrastructure ages. In [24], we test whether accounting for road repair needs could offer opportunities to boost conservation efficiency by piggybacking connectivity restoration projects on infrastructure maintenance. Using optimization models to align fish passage restoration sites with likely road repair priorities, we find potential increases in conservation return-on-investment ranging from 17% to 25%. Importantly, these gains occur without compromising infrastructure or conservation priorities; simply communicating openly about objectives and candidate sites enables greater accomplishment at current funding levels. Society embraces both reliable roads and thriving fisheries, so overcoming this coordination challenge should be feasible. Given deferred maintenance crises for many types of infrastructure, there could be widespread opportunities to enhance the cost effectiveness of conservation investments by coordinating with infrastructure renewal efforts.

  Due to a lack of resources, conservation organizations often depend on one species to indicate the presence of another. While extensive research has gone into methods for selecting these indicator species, few studies have directly measured the performance of indicator species in guiding conservation actions. In [28], we evaluated whether a small number of indicator species could be used to select barrier removal projects to restore breeding habitat access for migratory fishes in the highly fragmented tributaries of the North American Great Lakes. First, we used a newly-developed data set of the historical distributions of 35 species of native anadromous fishes to identify five clusters of co-occurring species, and then selected an indicator species for each cluster based on within-group co-occurrence. Next, we evaluated the utility of these five indicator species for guiding conservation projects, by using upstream habitat and removal costs for over 100,000 dams and road culverts across 1,800 tributaries of the Great Lakes. We compared the potential increase in accessible tributary habitat for each of the 35 native migratory species when barrier removals were prioritized to maximize benefits for 1) each species itself and 2) one of the five indicator species. We found that, for the majority of species, habitat gains from indicator-based project selection were at least 75% of the gains possible under species-specific planning. However, a few species received little habitat gain when indicators were used to choose projects. Overall, our findings suggest that indicator species can be an efficient basis for planning restoration efforts for a majority of the species of migratory fishes in the Great Lakes.

- In [25], we introduce an extended mathematical programming framework for specifying equilibrium problems and their variational representations, such as generalized Nash equilibrium, multiple optimization problems with equilibrium constraints, and (quasi-) variational inequalities, and computing solutions of them from modeling languages. We define a new set of constructs with which users annotate variables and equations of the model to describe equilibrium and variational problems. Our constructs enable a natural translation of the model from one formulation to another more computationally tractable form without requiring the modeler to supply derivatives. In the context of many independent agents in the equilibrium, we facilitate expression of sophisticated structures such as shared constraints and additional constraints on their solutions. We define a new concept, shared variables, and demonstrate its uses for sparse reformulation, equilibrium problems with equilibrium constraints, mixed pricing behavior of agents, and so on. We give some equilibrium and variational examples from the literature and describe how to formulate them using our framework. Experimental results comparing performance of various complementarity formulations for shared variables are given. Our framework has been implemented and is available within GAMS/EMP.

- In [26], we revisit the correspondence of competitive partial equilibrium with a social optimum in markets where risk-averse agents solve multistage stochastic optimization problems formulated in scenario trees. The agents trade a commodity that is produced from an uncertain supply of resources which can be stored. The agents can also trade risk using Arrow-Debreu securities. In this setting we define a risk-trading competitive market equilibrium and prove a welfare theorem: competitive equilibrium will yield a social optimum (with a suitably defined social risk measure) when agents have nested coherent risk measures with intersecting polyhedral risk sets, and there are enough Arrow-Debreu securities to hedge the uncertainty in resource supply. We also give a proof of the converse result: a social optimum with an appropriately chosen risk measure will yield a risk-trading competitive market equilibrium when all agents have nested strictly monotone coherent risk measures with intersecting polyhedral risk sets, and there are enough Arrow-Debreu securities to hedge the uncertainty in resource supply.

- In [27], we present a mixed complementarity problem (MCP) formulation of continuous state dynamic programming problems. We write the solution to the standard value function iteration (VFI) using projection as a Nash equilibrium between the approximation agent of the value function; and the maximization agent of the Bellman equation. The MCP approach replaces the iterative component of VFI with a one-shot solution to a square system of complementary conditions. Three numerical examples illustrate our approach and demonstrate that DP-MCP can significantly reduce the time required to solve VFI, without sacrificing model detail or solution accuracy.

- In [29] we present a stochastic optimization problem for a strategic major consumer who has flexibility over its consumption and can offer reserve. Our model is a bi-level optimization model (reformulated as a mixed-integer program) that embeds the optimal power flow problem, in which electricity and reserve are co-optimized. We implement this model for a large consumer of electricity in the New Zealand Electricity Market (NZEM). To reduce the solution time of the large mixed integer program, we explore the specific properties of the optimal power flow to reformulate the model. We show that by adding further constraints to tighten the LP relaxation we manage to improve the performance of the model.

- Global population and income trends continue to increase world food demand and an upscaling of diets to include more animal proteins. In response, cost and efficiency driven intensification of cropping and livestock operations has created substantive environmental concerns including deforestation, mono-culture versus diversified production systems, increased use of carbon intensive chemicals, increased greenhouse gas emissions, pathogen and antibiotic resistance health concerns, and nutrient runoff leading to large scale eutrophication and algal blooms. The paper [30] shows that management of nutrients within commodity crop and livestock production can provide improved agricultural sustainability. Specifically, optimization and data driven models are used to improve economic and environmental performance using a combination of nutrient cycling, reduced chemical fertilizer application, and logistical enhancements due to manure separation and precision nutrient blending/application technology. Farm field level data from regulatory instruments can be incorporated into a process model foundation using a sophisticated, large scale, mixed integer programming approach to generate a rich, linked decision space for evaluating economic and environmental performance tradeoffs. The paper also details how the operational model can be enhanced to include new environmental constraints that are more in line with the long term health of the land, air and water supply, and furthermore shows how the model can be used to quantify the costs of implementing new policies within an optimized system. In particular, the model can elucidate key strategic tradeoffs that can be used to understand the costs and effects of separation, and can demonstrate the utility of these approaches in dealing with increased regulation of organic nitrogen and dry matter. It also provides policy makers with science and data-based mechanisms to value the impact of specific regulations on both typical and specific farm setups, in a way that can be used directly in a regulatory setting.

2.6 Personnel supported

The following professional personnel received salary support from this grant:

2.6.1 Year 1

- Michael C. Ferris, Professor
- Olivier J. E. Huber, Research Associate
- Youngdae Kim, Research Assistant
- Stephen M. Robinson, Professor Emeritus

2.6.2 Year 2

- Michael C. Ferris, Professor
- Youngdae Kim, Research Assistant
- Stephen M. Robinson, Professor Emeritus

2.6.3 Year 3

- Michael C. Ferris, Professor
- Youngdae Kim, Research Assistant
- Stephen M. Robinson, Professor Emeritus
- Jiajie Shen, Research Assistant

3 Publications

This section reports the status of publications supported by this grant, or by its predecessor AFOSR Grant FA9550-10-1-0101 in case the publication process was not complete at the time the final report for that grant was submitted.

3.1 Papers published during period of performance

1. A. Tayyebi, T. D. Meehan, J. Dischler, G. Radloff, M. C. Ferris, and C. Gratton. SmartScape: A web-based decision support system for assessing the tradeoffs among multiple ecosystem services under crop-change scenarios. *Computers and Electronics in Agriculture*, 121:108–121, 2016. (Revised 2015).

2. Y. Liu, M. C. Ferris, and F. Zhao. Computational Study of Security Constrained Economic Dispatch with Multi-stage Rescheduling. *IEEE Transactions on Power Systems*, 30(2):920—-929, 2015 . (Revised 2015).

3. T. M. Neeson, M. C. Ferris, M. W. Diebel, P. J. Doran, J. R. OHanley, and P. B. McIntyre. Enhancing ecosystem restoration efficiency through spatial and temporal coordination. *Proceedings of the National Academy of Sciences*, 112(19):6236—-6241, 2015. (Revised 2015).

4. Stephen M. Robinson. Reduction of affine variational inequalities. *Computational Optimization and Applications*, DOI 10.1007/s10589-015-9796-7; published online 03 October 2015.

5. Y. Liu, M. C. Ferris, F. Zhao, T. Zheng, and E. Litvinov, "A Stochastic Unit Commitment with Derand Technique for ISO's Reserve Adequacy Assessment," in *2015 IEEE Power & Energy Society General Meeting*, Institute of Electrical & Electronics Engineers (IEEE), July 2015.

6. Y. Liu and M. C. Ferris, "Security Constrained Economic Dispatch using Semidefinite Programming," in *2015 IEEE Power & Energy Society General Meeting*, Institute of Electrical & Electronics Engineers (IEEE), July 2015.

7. D. K. Molzahn, Z. B. Friedman, B. C. Lesieutre, C. L. DeMarco, and M. C. Ferris, "Estimation of Constraint Parameters in Optimal Power Flow Data Sets," in *2015 North American Power Symposium (NAPS)*, Institute of Electrical & Electronics Engineers (IEEE), Oct. 2015.

8. A. B. Philpott, M. C. Ferris, and R. J. B. Wets, "Equilibrium, uncertainty and risk in hydro-thermal electricity systems," *Mathematical Programming B*, vol. 157, pp. 483–513, Jan. 2016.

9. M. C. Ferris and Y. Liu, "Modeling Demand Response in Organized Wholesale Energy Markets," *Optimization Methods and Software*, vol. 31, pp. 1064–1088, May 2016.

10. J. V. Outrata, M. C. Ferris, M. Červinka, and M. Outrata, "On Cournot-Nash-Walras equilibria and their computation," *Set-Valued and Variational Analysis*, vol. 24, no. 3, pp. 387–402, June 2016.

11. S. M. Robinson, "A short proof of the sticky face lemma," *Mathematical Programming Series B,* DOI 10.1007/s10107-016-1037-z, published online 13 June 2016.

12. F. Beaudry, M. C. Ferris, A. M. Pidgeon, and V. C. Radeloff, "Identifying areas of optimal multispecies conservation value by accounting for incompatibilities between species," *Ecological Modelling*, vol. 332, pp. 74–82, July 2016.

13. N. Vaish, M. C. Ferris, and D. Wood, "Optimization models for three on-chip network problems," *ACM Transactions on Architecture and Code Optimization*, vol. 13, no. 3, pp. 1–27, Sep. 2016.

14. L. Loewe, K. S. Scheuer, S. A. Keel, V. Vyas, B. Liblit, B. Hanlon, M. C. Ferris, J. Yin, I. Dutra, A. Pietsch, C. G. Javid, C. L. Moog, J. Meyer, J. Dresel, B. McLoone, S. Loberger, A. Movaghar, M. Gilchrist-Scott, Y. Sabri, D. Sescleifer, I. Pereda-Zorrilla, A. Zietlow, R. Smith, S. Pietenpol, J. Goldfinger, S. L. Atzen, E. Freiberg, N. P. Waters, C. Nusbaum, E. Nolan, A. Hotz,

R. M. Kliman, A. Mentewab, N. Fregien, and M. Loewe, “Evolvix BEST names for semantic reproducibility across code2brain interfaces,” *Annals of the New York Academy of Sciences*, vol. 1387, pp. 124–144, Dec. 2016.

15. A. T. Moody, T. M. Neeson, S. Wangen, J. Dischler, M. W. Diebel, M. Herbert, M. Khoury, E. Yacobson, P. J. Doran, M. C. Ferris, J. R. O’Hanley, and P. B. McIntyre, “Pet project or best project? Online decision support tools for prioritizing barrier removals in the Great Lakes and beyond,” *Fisheries*, vol. 42, pp. 57–65, Jan. 2017.

16. A. Del Pia, M. C. Ferris, and C. Michini, “Totally unimodular congestion games,” in *Proceedings of the Twenty-Eighth Annual ACM-SIAM Symposium on Discrete Algorithms*, Society for Industrial & Applied Mathematics (SIAM), Jan. 2017.

17. A. W. Milt, P. J. Doran, M. C. Ferris, A. T. Moody, T. M. Neeson, and P. B. McIntyre, “Local-scale benefits of river connectivity restoration planning beyond jurisdictional boundaries,” *River Research and Applications*, vol. 33, no. 5, pp. 788–795, Feb. 2017.

18. Y. Kim, O. Huber, and M. C. Ferris, “A Structure-Preserving Pivotal Method for Affine Variational Inequalities,” *Mathematical Programming*, vol. 168, pp. 93–121, Mar. 2017.

19. B. Park, J. Netha, M. C. Ferris, and C. L. DeMarco, “Sparse Tableau Formulation for Optimal Power Flow Applications,” ArXiv eprint arXiv:1706.01372, June 2017.

20. B. Park, L. Tang, M. C. Ferris, and C. L. DeMarco, “Examination of three different ACOPF formulations with generator capability curves,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2913–2923, July 2017.

21. M. T. Wortel, E. Noor, M. Ferris, F. J. Bruggeman, and W. Liebermeister, “Metabolic enzyme cost explains variable trade-offs between microbial growth rate and yield,” *PLOS Computational Biology*, vol. 14, no. 2, p. e1006010, Feb. 2018.

22. T. M. Neeson, P. J. Doran, M. C. Ferris, K. B. Fitzpatrick, M. Herbert, M. Khoury, A. T. Moody, J. Ross, E. Yacobson, and P. B. McIntyre, “Conserving rare species can have high opportunity costs for common species,” *Global Change Biology*, vol. 24, no. 8, pp. 3862–3872, Apr. 2018.

23. A. W. Milt, M. W. Diebel, P. J. Doran, M. C. Ferris, M. Herbert, M. L. Khoury, A. T. Moody, T. M. Neeson, J. Ross, T. Treska, J. R. O'Hanley, L. Walter, S. R. Wangen, E. Yacobson, and P. B. McIntyre, "Minimizing opportunity costs to aquatic connectivity restoration while controlling an invasive species," *Conservation Biology*, vol. 32, no. 4, pp. 894–904, May 2018.

3.2 Paper accepted during period of performance

24. T. M. Neeson, A. T. Moody, J. R. O'Hanley, M. W. Diebel, P. J. Doran, M. C. Ferris, T. Colling, and P. B. McIntyre, "Aging infrastructure creates opportunities for cost-efficient restoration of aquatic ecosystem connectivity," *Ecological Applications*, accepted, June 2018.

3.3 Papers in review or in revision at end of period of performance

25. Y. Kim and M. C. Ferris, "Solving equilibrium problems using extended mathematical programming," *Mathematical Programming C*, submitted, 2018.

26. M. C. Ferris and A. B. Philpott, "Dynamic risked equilibrium," *Operations Research*, submitted, 2018.

27. W. Chang, M. C. Ferris, Y. Kim, and T. F. Rutherford, "Solving stochastic dynamic programming problems: a mixed complementarity approach," *Computational Economics*, submitted, 2018.

28. K. Fitzpatrick, A. Moody, A. Milt, M. Herbert, M. Khoury, E. Yacobson, J. Ross, P. Doran, M. Ferris, P. McIntyre, and T. Neeson, "Can indicator and umbrella species guide conservation investments to restore connectivity in great lakes tributaries?," *Biological Conservation*, submitted, 2018.

29. M. Habibian, G. Zakeri, A. Downward, M. F. Anjos, and M. Ferris, "Co-optimization of demand response and reserve offers," submitted, 2018.

30. A. Christensen, H. Dong, J. Ramakrishnan, M. Sharara, and M. Ferris, "Valuation of technology options for nutrient management under different environmental policy regimes," submitted 2017; in revision.

3.4 Papers completed under AFOSR Grant FA9550-10-1-0101 but not published by date of final report for that grant

31. L. M. Tang and M. C. Ferris. A Hierarchical Framework for Long-Term Power Planning Models. *IEEE Transactions on Power Systems*, 30:46–56, January 2015. (Completed under previous funding).

32. Y. Liu, J. Holzer, and M. C. Ferris. Extending the Bidding Format to Promote Demand Response. *Energy Policy*, 86:82–92, November 2015. (Completed under previous funding).

33. E. Ritz, D. D. Pollard, and M. C. Ferris. The influence of fault geometry on small strike-slip fault mechanics. *Journal of Structural Geology*, 73:49—-63, April 2015. (Completed under previous funding).